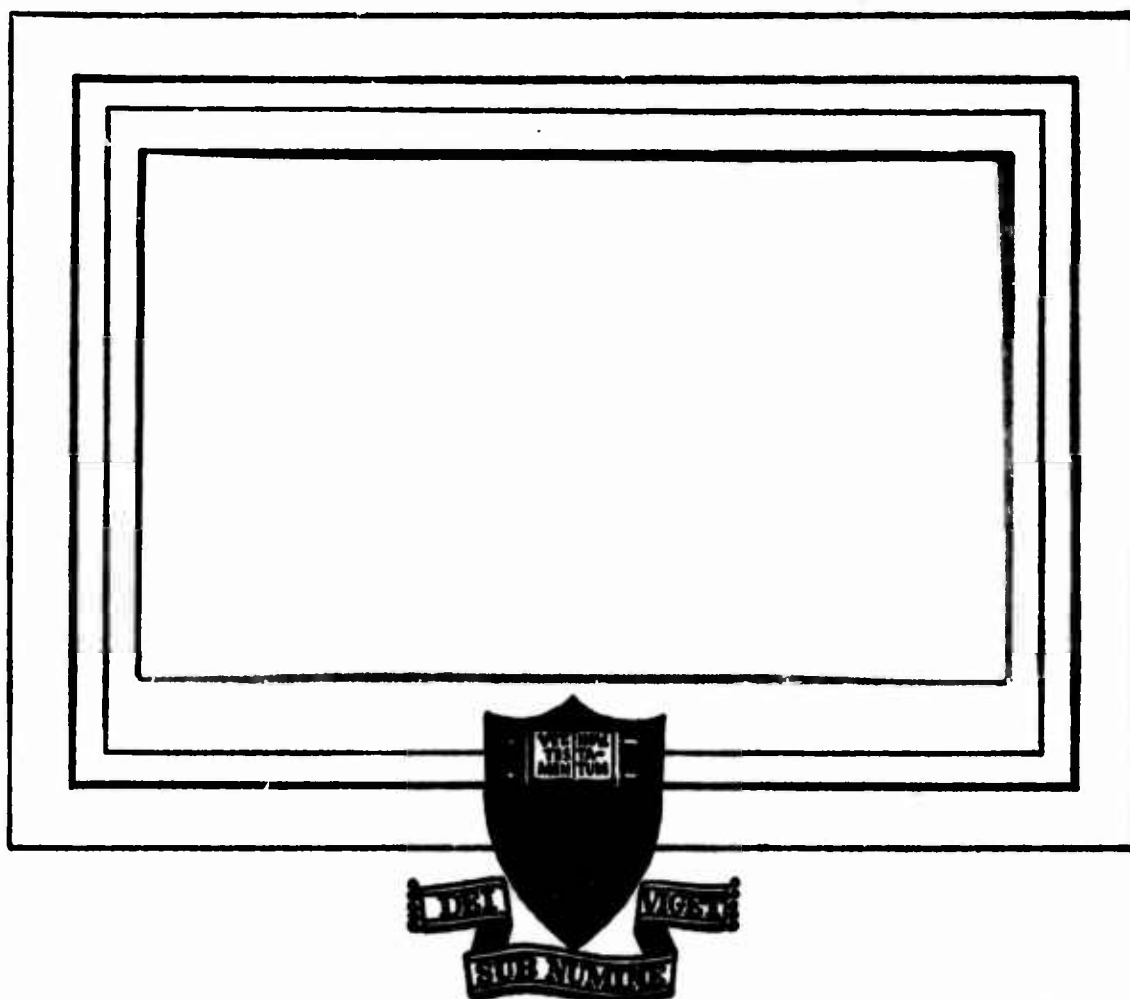


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OFFICE OF NAVAL RESEARCH

Contract USN-Nonr 1858(29)
NR 094-200

HEAT TRANSFER IN OSCILLATING FLOW
FINAL REPORT

Department of Aerospace and Mechanical Sciences
Report 483-g

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15 October 1967

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Introduction

The purpose of this final report is to summarize the research effort on Heat Transfer in Oscillating Flow sponsored at Princeton University since 1958 by the Office of Naval Research. The contract monitor at ONR for the past several years has been Mr. Roland Jackel.

Technical reports have been issued throughout this research endeavor which cover the experimental and theoretical correlations in considerable detail. Only the briefest of summaries of that work will be covered in this report.

Discussion and Conclusions of the Research

From the beginning, because of the theoretical complications associated with the phenomena of heat transfer in oscillating flow, the research was conceived as a primarily experimental effort. Until it could be established exactly what processes were responsible for the variations in heat transfer in the presence of gas flow oscillations no theoretical approach was possible. Hence when this research was initiated at Princeton, the first objective was to show, in a fully-developed oscillating environment (Reynolds number $\sim 200,000$), that heat transfer under unsteady conditions was significantly different from steady-state heat transfer. Unstable combustion devices, especially rocket motors, had indicated significant heat transfer increases, but the role of combustion in those cases had not been determined.

In the early experiments described in Reference 1, nonresonant oscillating conditions were achieved in a 100-inch length, 1 1/2 inch diameter duct. Covering a broad frequency range (~ 50 to 5000 Hz), those tests indicated significant heat transfer increases could be achieved

(local increases to 70% of steady-state) from the gas dynamics and in the absence of combustion.

For several years the experimental approach depended upon a heated nichrome strip (axial length 1/2 inch, buried flush with the duct wall) to probe the local heat transfer rates. The oscillations were produced by a siren at the exit end of the duct (closed-end acoustic condition) with the gas flow regulated by a sonic orifice and passing through a plenum chamber into the upstream end of the duct (open-end condition). The upstream reflecting condition was modified by the insertion of screens to result in a nonresonant duct configuration. Removal of the screens allowed a wide range of resonant frequencies to be achieved. Peak-to-peak amplitudes reaching maximums of approximately 30% of the steady-state pressure were recorded at the standard frequency of 280 Hz (7th harmonic).

In the resonant duct experiments that were reported in References 1 and 2, the heat transfer rate increases recorded with the nichrome heating element were shown to be maximized at the unsteady velocity antinode locations, which for longitudinal modes are also the pressure nodes. Heat transfer increases at those preferred locations were greater than 100%. Those results agreed in general with observations of axial heat transfer profiles from rocket motor firings which experienced longitudinal mode combustion instability.

Following the measurements at a limited number of discrete axial locations, reported in Reference 2, the experimental apparatus was upgraded through the incorporation of an axial traversing heater section. Reference 3 describes the tests with this apparatus which allowed heat transfer and velocity profiles over at least a quarter wave length for the seventh longitudinal harmonic (standard frequency) and higher modes. In those tests the

possibility of the generation of transverse modes within the duct was also investigated and reported in References 3 and 4.

The first comprehensive series of experiments in heat transfer with oscillating flow in the duct with the traversing heater section and revised instrumentation were reported in Reference 5. The experimental approach, which enabled a continuous heat transfer survey to be made between node and antinode locations, was aided by direct plotting on IBM 7090 computing equipment. The gap variation method (where both the siren gap and the size of the downstream sonic orifice were adjustable) allowed duct Mach number and unsteady pressure amplitude to be varied independently for the first time in the program. Those tests revealed that, in addition to the maximum heat transfer augmentation at the velocity antinode location, the degree of flow reversal (which was dependent on the duct Mach number and the amplitude of the unsteady velocity) was another important factor in achieving maximum heat transfer from the heater. The local heat transfer increases reached sizable values in those tests (often heat transfer increases of considerably more than 100% were recorded). Those increases may be traced to "front end effects", i.e., within the cycle cool core gases sweep alternately from one side to the other across the relatively narrow heater strip, thus enhancing the local heat transfer.

The most complete experimental analysis seeking the mechanisms responsible for the unsteady heat transfer associated with fully-developed turbulent flow was described in Reference 6. In that reference a dimensional analysis of the problem was carried out to establish the important non-dimensional parameters. Several possible mechanisms by means of which longitudinal standing-wave oscillations superimposed on steady flow in a

pipe could affect that flow were discussed; included were viscous dissipation, acoustic streaming and the effects of the oscillations on the turbulence exchange properties in the flow. A very simple quasi-steady analysis was also described.

Pertinent literature was surveyed in considerable detail in Reference 6 with regard to the non-dimensional parameters, and the mechanisms mentioned. Experimental heat transfer measurements in a pipe flow with superimposed longitudinal standing-wave oscillations were described where the heated section extended through both node and antinode locations. In essentially the same experimental apparatus, hot-wire measurements of the time-average and peak-to-peak velocity profiles in the pipe were made and were described in the report. Those heat transfer and hot-wire measurements, together with data from the literature are discussed as a means to determine the importance of viscous dissipation and acoustic streaming as the mechanisms through which the oscillation affects the heat transfer in the flow. For many cases of interest, these two phenomena appear to be unimportant.

The discussion of the heat transfer and hot-wire measurements and the relationship to the effects of the oscillations on the turbulence exchange properties of the flow was one of the most important aspects of Reference 6. Eddy diffusivity profiles were computed which provided information on the regions of generation of 'abnormal' turbulence by the oscillation as well as subsequent diffusion and decay of that turbulence. While those eddy diffusivity profiles were somewhat uncertain, due to many possible causes of error, the picture of the development of the 'abnormal' turbulence which emerged through their use was consistent with the known structure of the oscillation and with the heat transfer data. From that analysis,

as well as from other evidence, the effects of the oscillation on the turbulence exchange properties appear as the important mechanism through which the oscillation affected heat transfer in the flow.

Also in Reference 6, attempts were made to correlate the heat transfer data of that study and other data from the literature using the non-dimensional parameters. Some evidence, both theoretical and experimental, suggested that in certain restricted cases, the heat transfer data could be approximately correlated using only two of the four main non-dimensional parameters; however, insufficient data was available to make that conclusion more than very tentative, and in any case, large variations of the remaining two parameters would be expected to have substantial effects on the heat transfer. In a certain parameter range, some of the heat transfer data shows a remarkable approach to predictions based on the very simple quasi-steady theory previously mentioned; it would appear that certain restricted regions of the flow were approaching quasi-steady conditions in those cases.

Recommendations were given in Reference 6 for further research; and finally, a brief discussion was included on the possible applications of the effects of oscillations on heat transfer observed in this study to heat exchanger design. It was concluded that the opportunities to apply longitudinal fluid oscillations to improve the performance of heat exchangers operating with turbulent gas flow in pipes are very limited.

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)		
1. ORIGINATING ACTIVITY (Corporate author) Princeton University Guggenheim Laboratories, Forrestal Campus Princeton, N.J. 08540		2a. REPORT SECURITY CLASSIFICATION Unclassified
		2b. GROUP
3. REPORT TITLE HEAT TRANSFER IN OSCILLATING FLOW - FINAL REPORT		
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Final Report 1958 to October 1967		
5. AUTHOR(S) (First name, middle initial, last name) David T. Harrje		
6. REPORT DATE October 15, 1967	7a. TOTAL NO. OF PAGES 6	7b. NO. OF REFS 6
8a. CONTRACT OR GRANT NO. USN-Nonr 1858(29)	8a. ORIGINATOR'S REPORT NUMBER(S) Department of Aerospace and Mechanical Sciences Rept. 483-g	
b. PROJECT NO. NR 094-200		
c.	8b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	
d.		
10. DISTRIBUTION STATEMENT Distribution of this document is unlimited		
11. SUPPLEMENTARY NOTES		12. SPONSORING MILITARY ACTIVITY Office of Naval Research Power Branch, Washington, D.C. 20360
13. ABSTRACT A brief summary is provided of an extensive research into heat transfer with oscillating flow. Significant heat transfer increases were demonstrated without combustion. Measurements were made in a turbulent, unsteady environment provided within a duct which was placed in longitudinal mode resonance by a siren arrangement. Importance of the velocity antinode locations and the degree of flow reversal in the enhancement of heat transfer was indicated. Measurement techniques utilized a heated strip, axially traversing the tube between node and antinode locations; a steam-heated axially-segmented test section which covered more than one wave length of the imposed oscillations; and constant-temperature hot-wire probe surveys of the core and boundary layer in both the steady-state and unsteady duct environments. The mechanism which best correlated the experimental measurements and analyses was the effect of the oscillations on the turbulence exchange properties, while viscous dissipation and acoustic streaming appeared to be unimportant for many cases of interest.		

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Unsteady Heat Transfer						
Heat Transfer Mechanisms						
Resonating duct						
Acoustic streaming						
Viscous dissipation						
Turbulence structure						
Flow reversal						
Velocity antinodes						
Non-resonating duct						
Traversing heater						
Application of unsteady heat transfer						